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AUTHOR(S): B. F. Gibson, T-5

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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ΛN-ΣN COUPLING IN S-SHELL Λ-HYPERNUCLEI

B. F. Gibson
Theoretical Division, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

The inclusion of ΛN-ΣN coupling in the A=4 Λ-hypernuclei is shown to be required in order to obtain proper ordering of the 0^+ ground state and 1^+ spin-flip excited state, when exact four-body equations are solved. It is argued that suppression of the off-diagonal ΛN-ΣN coupling in the A=5 system, similar to that in the A=4 isodoublet, should account for the anomalously small binding of ${}^5_\Lambda$He. An alternative quark model explanation is also considered.

INTRODUCTION

Nuclear physicists seek to understand the fundamental forces of nature and the roles of these forces in determining the structure of nuclei. In addition to providing an expedient means of looking beyond that form of matter found in nature, the study of hypernuclear physics will provide 1) important new information about the strong and weak nuclear forces and 2) further improvement of our microscopic picture of nuclear matter through use of the strange baryon (or s quark) as a tagged probe.

Nuclear physics has dealt with nuclei and their interactions at interparticle distances corresponding to conditions which might be described as two bags of quarks barely overlapping. Here, where the asymptotically free theories of QCD may have difficulty in describing the observed phenomena, the nuclear physicist has found a modicum of success and simplification in terms of a picture involving only the physically observable baryons and mesons. However, our understanding is far from complete. Because of this and our desire to learn where the transition to the quark matter picture occurs, we seek measureable effects due to the quark structure of matter. To that end, we must first define the limits of validity for describing nuclear phenomena in terms of the observed hadrons before evidence for quark degrees of freedom can be critically evaluated.

A good test lies in modeling the anomalously small binding of ${}^5_\Lambda$He, which has been an enigma for twenty years. In the baryon picture, the Λ is distinguishable. All five baryons can coexist in 1s states to form the ground state. (This is in contrast to ^{5}He where only four of the five nucleons can reside in the 1s shell, and consequently ^{5}He is unbound.) Nonetheless, simple model calculations based upon a ΛN interaction parameterized to account for the low-energy ΛN scattering data overbind ${}^5_\Lambda$He by 2-3 MeV. The separation energy of the Λ is a factor of 2 too large. Nuclear physicists have sought an explanation in terms of 1) the strong ΛN-ΣN coupling that is known to exist and 2) tensor forces which bind the triton and alpha particle less compared to the deuteron than do central force models. However, the quark picture offers an alternative explanation. Only the s quark of the Λ is distinguishable and can therefore coexist in a 1s state with the 12 u and d quarks of the ^{4}He core. The accompanying u and d quarks of the Λ are Pauli blocked from 1s states. Thus, one might expect that the binding of $^5_\Lambda$He should be smaller than one would estimate based upon knowledge of Λ-N scattering or binding energies of $^3_\Lambda$H and $^4_\Lambda$H, where the u and d quarks of the Λ are not Pauli blocked. Is the hadron picture unable to account for the $^5_\Lambda$He binding anomaly? Let us consider first a model study of the A=4 system.

The A=4 0^+-1^+ Binding Energy Difference

The A=4 hypernuclei provide a rich source of information about the hyperon-nucleon (YN) force.[1] The (spin-flip) excitation energies are quite sensitive to the ΛN-ΣN coupling in the YN interaction. In particular, if one represents the free YN interaction in terms of one-channel effective ΛN potentials, the resulting 0^+ (ground) state and 1^+ (excited) spin-flip state are inversely ordered, the 1^+ state being more bound. It is the "Σ suppression" that results from the reduced strength of the ΛN-ΣN off-diagonal potential embedded in a composite trinucleon core which we study here as a means of explaining the correct ordering.

The lack of precision hyperon-nucleon scattering data has been a severe limitation upon any attempt to quantitatively characterize that interaction. Commendable attempts have been made to parameterize potentials using 1) a combined analysis of all existing YN data plus the extensive NN data and 2) various symmetry assumptions concerning meson coupling in an OBE model of the YN and NN interactions.[2,3] We make use here of the ΛN-ΣN separable potential model of Stepien-Rudza and Wycech,[4] which is based upon the main features of the Nijmegen OBE potential of Ref. 3.

To understand the importance of ΛN-ΣN coupling, we consider first the model that results when it is ignored. That is, we first assume that the free YN force acts without modification in composite systems. Such a model has been employed extensively in s-shell hypernuclear studies throughout the literature; e.g., see Ref. 5. Such a phenomenological approach leads to the following spin-isospin combinations of the effective ΛN spin-singlet and spin-triplet potentials $\bar{V}^s_{\Lambda N}$ and $\bar{V}^t_{\Lambda N}$:

$$^4_\Lambda\mathrm{H}(S=0):\ V_{YN}=\tfrac{1}{2}\bar{V}^s_{\Lambda N}+\tfrac{1}{2}\bar{V}^t_{\Lambda N} \qquad {}^4_\Lambda\mathrm{H}^*(S=1):\ V_{YN}=\tfrac{1}{6}\bar{V}^s_{\Lambda N}+\tfrac{5}{6}\bar{V}^t_{\Lambda N}\ . \quad (1)$$

We neglect any charge-symmetry-breaking differences between Λp and

Λn forces. We assume that the singlet interaction is stronger than the triplet,[5] so that the ground state has S=0. The YN subscript denotes the fact that the potential describes the full effective ΛN-ΣN interaction. The implicit assumption is that the ΛN-ΣN coupling is identical in each state. That is, one has assumed that the 2×2 matrix potentials

$$V^s_{YN} = \begin{matrix} V^s_{\Lambda N} & V^s_{XN} \\ V^s_{XN} & V^s_{\Sigma N} \end{matrix} \quad \text{and} \quad V^t_{YN} = \begin{matrix} V^t_{\Lambda N} & V^t_{XN} \\ V^t_{XN} & V^t_{\Sigma N} \end{matrix} \tag{2}$$

can be approximated by effective one-channel potentials $\bar{V}^s_{\Lambda N}$ and $\bar{V}^t_{\Lambda N}$ independent of the spin of the hypernuclear states under study. Such is not the case. For the A=4 hypernuclei (with T=½ nuclear cores) the $J^\pi=0^+$ ground-state potentials are of the form

$$V^s_{YN} = \begin{matrix} V^s_{\Lambda N} & \frac{-1}{3}V^s_{XN} \\ \frac{-1}{3}V^s_{XN} & V^s_{\Sigma N} \end{matrix} \quad \text{and} \quad V^t_{YN} = \begin{matrix} V^t_{\Lambda N} & V^t_{XN} \\ V^t_{XN} & V^t_{\Sigma N} \end{matrix}, \tag{3}$$

while the $J^\pi=1^+$ excited-state potentials are of the form

$$V^s_{YN} = \begin{matrix} V^s_{\Lambda N} & V^s_{XN} \\ V^s_{XN} & V^s_{\Sigma N} \end{matrix} \quad \text{and} \quad V^t_{YN} = \begin{matrix} V^t_{\Lambda N} & \frac{1}{5}V^t_{XN} \\ \frac{1}{5}V^t_{XN} & V^t_{\Sigma N} \end{matrix}. \tag{4}$$

(See, for example, Ref. 6 and 7.) In neither case is the coupling of the Λ-Σ system to the composite isospin-½ trinucleon core the same as the coupling to an elementary isospin-½ nucleon. The singlet potential differs from the free interaction in the ground state. The triplet potential differs from the free interaction in the excited state. In each case the magnitude of the ΛN-ΣN coupling is reduced, weakening the YN interaction relative to its free strength.[1] Both the 0^+ and 1^+ state binding energies are less than those calculated in terms of a model based entirely upon free ΛN interaction parameters.

The measurement of the γ-transitions in the A=4 hypernuclei has been described by Piekarz;[3] see also Ref. 9 and 10. Such bound-state transitions provide invaluable data because one's ability to calculate bound state properties is much better developed than for continuum states. The reported M1 spin-flip transition energies are

$$E_\gamma(^4\mathrm{H}) = 1.04\pm.04\ \mathrm{MeV} \quad \text{and} \quad E_\gamma(^4\mathrm{He}) = 1.15\pm.04\ \mathrm{MeV}. \tag{5}$$

These excitation energies (approximately 1 MeV) imply that the mechanism leading to the 0^+-1^+ splitting must be similar for each member of the isodoublet. The question we address is whether E_Y can be understood, at least qualitatively, in terms of the known properties of the free YN interaction.

In order to carry out calculations within the context of an exact four-body formalism,[11] we utilize rank-one separable potential representations of both the NN and YN interactions.[12] The procedure adopted is to accept the free interactions defined by the rank-two potentials of Ref. 4, to modify the off-diagonal coupling terms as noted above for the ground state and the excited state, and to generate effective rank-one potentials which reproduce the same scattering length and effective range as the corresponding modified singlet and triplet rank-two potentials. The result is a reasonable qualitative description of the spin-isospin Σ-suppresion (compared to the free interaction) in the A=4 ground state and excited state potentials.

The exact, coupled two-variable integral equations that must be solved, when the NN and YN interactions are represented by separable potentials, are described in Ref. 11. The resulting numerical solutions possess the characteristics of true few-body calculations: for an attractive potential with a negative scattering length, $|a|>|a'|$ implies that V is more attractive than V′ in two-body, three-body, and four-body calculations, whereas $r > r'$ (effective range) implies that V is more attractive than V′ in a two-body calculation but less attractive in both three-body and four-body calculations. Even though this is an oversimplified picture, it does provide a correct qualitative explanation of the E_Y results described below in terms of the a and r values of the simple potentials involved.

The scattering lengths and effective ranges of the interactions used in the calculation are tabulated in Table I. The first two columns list the parameters of the free interactions as defined in Ref. 4; our calculated a and r differ slightly from their reported values. The parameters in the third and fourth columns correspond to the rank-two potentials with off-diagonal matrix elements modified as described above for the 0^+ ground state ($V^s_{XN}\to -\frac{1}{3}V^s_{XN}$) and the 1^+ excited state ($V^t_{XN}\to\frac{1}{5}V^t_{XN}$). These scattering parameters were used to generate the rank-one separable potentials

Table I. Scattering lengths and effective ranges for the free-space potentials and A=4 potentials

	V^s_{YN}	V^t_{YN}	$V^s_{YN}(0^+)$	$V^t_{YN}(1^+)$
a (fm)	-1.97	-1.95	-1.33	-0.95
r (fm)	3.80	2.45	4.68	3.51

which were employed in our exact four-body calculations. The free singlet potential is stronger than the triplet in the two-body sense: $|a_s|>|a_t|$ and $r_s > r_t$. However, the significant difference in size between r_s and r_t ensures that the triplet dominated 1^+ state is more bound than the 0^+ state, when potentials defined by the free scattering parameters are used. Indeed, we find E_γ=-1 MeV, which has the wrong sign. That is, the 1^+ state is one MeV more bound than the 0^+ state, if effective interactions parameterized according to the free YN scattering data are used in a true four-body calculation. To obtain a correct picture, one must take into account the spin-isospin suppression of the off-diagonal potentials outlined above. When the 0^+ modified singlet potential is combined with the free-space triplet, the 0^+ binding energy is lowered to about 9 MeV. Correspondingly, when the 1^+ modified triplet potential is combined with the free-space singlet, the 1^+ binding energy is lowered even further to around 7.7 MeV.

In summary, we obtain the following ground state Λ-separation energy and γ-transition energy:

$$B_\Lambda = B({}^4_\Lambda H) - B({}^3H) \cong 2.0 \text{ MeV} \tag{6}$$

$$E_\gamma(1^+\to 0^+) = B({}^4_\Lambda H) - B({}^4_\Lambda H^*) \cong 1.3 \text{ MeV} . \tag{7}$$

These results are qualitatively correct and a clear indication of the importance of treating explicitly ΛN-ΣN coupling in hypernuclear studies, if one wishes to understand these systems in terms of the fundamental YN interactions defined by the free scattering data.

The ${}^5_\Lambda$He Binding Energy

Because the Λ is distinguishable in the baryon-meson picture of nuclear physics, the YN interaction appropriate to the A=5 system is of the same form as that utilized in the A=4 study. However, the Σ-suppression is even more significant in ${}^5_\Lambda$He than in the A=4 isodoublet.[13] The ^{4}He core and ${}^5_\Lambda$He have isospin 0 as does the Λ. However, the Σ has isospin 1 and cannot couple directly to the ground state of the ^{4}He core to form ${}^5_\Lambda$He. The Σ must couple to the even parity T=1 excited states of the ^{4}He core. These are very high up in the spectrum. Therefore, the ΛN-ΣN coupling is strongly suppressed. In an approximation consistent with that used for the A=4 calculation one would represent the interaction as

$$V_{YN}^{s,t} = \begin{matrix} V_{\Lambda N}^{s,t} & 0 \\ 0 & V_{\Sigma N}^{s,t} \end{matrix} \tag{8}$$

completely suppressing the Λ-Σ conversion. Thus one would anticipate that the Λ-separation energy $B_\Lambda({}^5_\Lambda\mathrm{He})$ in such a model calculation would be significantly less than the value of 5-6 MeV obtained in model calculations employing the free-space potentials.

Are there quark effects to be seen in the binding of ${}^5_\Lambda$He? At first thought the Pauli blocking from the 1s shell of the u and d quarks of the Λ by the 12 u and d quarks of the ^{4}He core would argue for a reduction in binding from models based upon free YN scattering, where no u,d Pauli blocking occurs. If quark confinement is absolute so that the s is constrained to follow the u and d, should not a ^{5}He type picture, in which the last baryon (last 3 quarks) is blocked from the 1s shell leading to no bound state, be expected? Can dropping the s quark into the 1s shell produce binding in ${}^5_\Lambda$He when substituting an s for a d in ^{4}He to form ${}^4_\Lambda$He lowers the binding? Many interesting questions concerning the comparison of the hadron and quark model approaches remain open.

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